

WTEC Panel on

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WTEC Panel on Spin Electronics (“Spintronics”)

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ABSTRACT

This report is a comparative review of spin electronics (“spintronics”) research and development activities in the United States, Japan, and Western Europe conducted by a panel of leading U.S. experts in the field. It covers materials, fabrication and characterization of magnetic nanostructures, magnetism and spin control in magnetic nanostructures, magneto-optical properties of semiconductors, and magnetoelectronics and devices. The panel’s conclusions are based on a literature review and a series of site visits to leading spin electronics research centers in Japan and Western Europe. The panel found that Japan is clearly the world leader in new material synthesis and characterization; it is also a leader in magneto-optical properties of semiconductor devices. Europe is strong in theory pertaining to spin electronics, including injection device structures such as tunneling devices, and band structure predictions of materials properties, and in development of magnetic semiconductors and semiconductor heterostructures. The United States is a leader in optoelectronics including optical detection and injection, as well as novel instrumentation — e.g., ballistic electron magnetic microscopy (BEEM). The United States is also the international leader in applications including read heads, magnetic random access memory (MRAM), sensors, and magnetic device production. Additional details are included in an executive summary conveying the panel’s overall conclusions.

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PREFACE

The history of scientific research and technological development is replete with examples of breakthroughs that have advanced the frontiers of knowledge, but seldom does it record events that constitute paradigm shifts in broad areas of intellectual pursuit. One notable exception, however, is that of spin electronics (also called spintronics, magnetoelectronics or magnetronics), wherein information is carried by electron spin in addition to, or in place of, electron charge. It is now well established in scientific and engineering communities that Moore's Law, having been an excellent predictor of integrated circuit density and computer performance since the 1970s, now faces great challenges as the scale of electronic devices has been reduced to the level where quantum effects become significant factors in device operation. Electron spin is one such effect that offers the opportunity to continue the gains predicted by Moore's Law, by taking advantage of the confluence of magnetism and semiconductor electronics in the newly emerging discipline of spin electronics.

From a fundamental viewpoint¹, spin-polarization transport in a material occurs when there is an imbalance of spin populations at the Fermi energy. In ferromagnetic metals this imbalance results from a shift in the energy states available to spin-up and spin-down electrons. In practical applications, a ferromagnetic metal may be used as a source of spin-polarized electrons to be injected into a semiconductor, a superconductor or a normal metal, or to tunnel through an insulating barrier. Then, depending on the magnetization direction of a material, relative to the spin polarization of the electrons, a material can function either as a conductor or an insulator for electrons of a specific polarization.

The use of both charge and spin degrees of freedom in semiconductors is expected to enable a revolutionary class of electronics whose functionality will surpass that of existing semiconductor technology. Spin electronics combines semiconductor microelectronics with spin-dependent effects that arise from the interaction between electrons and a magnetic field. Since the characteristic length for spin-dependent effects is on the order of 1 nm compared to 10 nm for semiconductor electronics, spin-electronic devices have the potential to achieve much higher integration densities. Conventional electronics is based on the number of charges and their energies, and device performance is limited in speed due to energy dissipation, whereas spin electronics is based on the direction of spin and spin coupling, and is capable of much higher speeds at low power consumption. The advantages of spin-electronic devices would include non-volatility permitting data retention in non-powered conditions, increased integration densities, higher data processing speeds, low electrical energy demands, and fabrication processes compatible with those currently used in semiconductor microelectronics. There is strong evidence that the technology shift taking place from semiconductor electronics to spin-dependent devices will help to meet the sensing and storage demands of information technology in the 21st century. During the next decade, spin electronics will accelerate development in quantum computing, communications, and revolutionary molecular and chemical systems.

To date, the principal applications of spin-electronic devices have been in read heads for magnetic discs, and in magnetic field sensors. However, the greatest impact of spin-electronic devices is expected to be in magnetic random access memories (MRAM) to be used in conjunction with, or as replacements for, EEPROM (electrically erasable, programmable read-only memory) and flash memory in computer applications, where MRAM's lower writing energy, faster writing times, and no wear-out with writing cycle become significant factors. Although prototype MRAM devices have been employed in niche applications, commercial quantities of MRAM are not yet available. However, several industrial companies in the United States and abroad are poised to make substantial market introduction of MRAM products by the year 2004.

Recognizing the importance of the field of spin electronics and the potential impact that this new technology will have on the competitiveness of the United States in the global economy, the National Science Foundation in conjunction with the Office of the Secretary of Defense, the Defense Advanced Research

¹ Prinz, G. 1998. *Science* 89, 260.

Projects Agency, the Office of Naval Research, and the National Institute of Standards and Technology, commissioned a worldwide study of the status of spin electronics with particular emphasis on the United States, Japan and Europe. The study was conducted by the World Technology Evaluation Center (WTEC), Inc. utilizing a panel of five experts from United States universities and industry. The panel consisted of Stephan von Molnár, Michael L. Roukes, Robert A. Buhrman, David D. Awschalom, and James M. Daughton, and was supported by participants from several Federal Agencies. Not only did the panel compile a comprehensive literature survey and analysis, but numerous interviews and team site visits to industries, universities, and government laboratories were conducted. The panel summarizes its broad conclusions in the Executive Summary, wherein it is noted that Japan is clearly the leader in new material synthesis, characterization and predictive calculation, while theory pertaining to spin electronics and spin-electronic devices is well developed in Europe. By comparison, the United States is the leader in optoelectronics and novel diagnostic instrumentation.

Chapter 1, written by Professor Stephan von Molnár, poses the question “Spin Electronics – is it the Technology of the Future?” Prof. von Molnár provides an excellent rationale for the conduct of the WTEC study, and comes away with the conclusion that the manifestation of spin electronics in semiconducting hybrid devices represents a vibrant new direction, and that semiconductor spin electronics will play an important role in the future to advance the frontiers of information technology. In Chapter 2, von Molnár reviews materials activities in spin electronics, and concludes that much of the new materials research effort is driven by innovations that can be traced to Japanese leadership in materials development in perovskites and to Japan's early decision in 1996 to fund spin-controlled semiconductor nanostructures at a level of \$6 million. Prof. von Molnár goes on to laud both DARPA (Defense Advanced Research Projects Agency) and NSF (National Science Foundation) for their support of research in materials synthesis and fabrication.

Professor Michael L. Roukes provides, in Chapter 3, an enlightening account of fabrication and characterization of magnetic nanostructures, addressed from both the conventional “top down” and the emerging “bottom up” perspectives. Roukes also summarizes techniques and instrumentation used in the characterization of magnetic nanostructures, and underscores the importance of work in imaging being conducted both in Europe and Japan. Further, Roukes observes that the United States has centers of excellence broadly covering imaging techniques, and is particularly strong in entrepreneurial frontier activities.

In Chapter 4, Professor Robert A. Buhrman provides a concise account of the state-of-the art in spin dynamics including spin injection, spin transport and spin transfer, noting that research in these areas is being actively pursued by a number of laboratories in Japan and Europe. Buhrman makes special note of the well-equipped thin-film growth and nanofabrication laboratories in Japan that can be expected to result in major contributions in spin electronics in the years ahead. Buhrman also observes that Europe's extensive expertise in magnetism, electronic and magnetic materials, and mesoscopic physics portends an upcoming decade of high productivity and keen competition on a worldwide basis in the area of spin electronics.

The optoelectronic manipulation of spin in semiconductors is authoritatively treated in Chapter 5 by Professor David D. Awschalom, who notes at the outset that an additional degree of freedom afforded by semiconductor spintronics allows direct optical access to electronic and nuclear-spin states. In addition to providing general conclusions on the emerging global effort in developing optoelectronic applications of spintronics in Japan, Europe and the United States, Awschalom takes the opportunity to identify several interesting new lines of research and potential applications. Among these may be listed spin-based semiconductor qubits for use in practical quantum processors; spin transistors that combine memory and logic functions where the amplitude and phase of the net spin current can be controlled by either electric or magnetic fields; and ferromagnetic materials used to imprint nuclear spins in semiconductors, thereby offering an additional pathway for manipulating and storing information at the atomic scale.

In the concluding chapter (Chapter 6), Dr. James M. Daughton, from the industrial sector, deals with the salient features of magnetoelectronics device research in Europe and Japan, and contrasts the findings with research conducted in the United States. Daughton traces the development of magnetoresistive structures from AMR (anisotropic magneto-resistance) to GMR (giant magnetoresistance) and to MTJ

(magnetoresistive tunnel junctions) pointing out the rapid application of these new structures in sensors, read heads, galvanic isolators and non-volatile memories (MRAM). In overview, Daughton concludes that device application work in the United States is stronger than that in Japan or Europe, and delineates industrial companies involved in device manufacture and sale. However, in very high magnetoresistive structures, both Japan and Europe lead the United States in published work.

Each chapter of this book is supported by a comprehensive list of references, which in total covers all aspects of spin electronics, spintronics, magnetoelectronics and magnetronics in the United States, Japan, Europe, and other countries. The highlights of this study are to be found in the appendices that range all the way from biographical information on the authors, who are also the WTEC panel members (Appendix A), to site-visit reports on Europe (Appendix B), and on Japan (Appendix C).

I personally had the privilege as a government participant representing the National Science Foundation of accompanying the panel members on several visits to Japanese companies and universities, and I can attest to the wealth of information that is contained in the site-visit reports in Appendices B and C. Of equal interest to the reader should be Appendix D: Highlights of Recent U.S. Research and Development Activities.

It has been for me a most interesting and rewarding experience and a privilege to participate in the WTEC study of spin electronics in the United States, Japan and Europe. Not only did I function as a government sponsor, but also as a visitation team member and planner. During all this time I had the opportunity to interact with the WTEC panelists, and I continue to be impressed with the quality and insight of the panel members and the high regard in which they are held by members of the worldwide spin-electronics community. An added feature of many of my visits and review activities involved graduate students from home and abroad, so that I had many opportunities to encourage the integration of research and education at the graduate level consistent with National Science Foundation policy in this area.

My thanks go to Dr. Stuart A. Wolf of DARPA (Defense Advanced Research Projects Agency), Dr. William F. Egelhoff Jr. of NIST (National Institute of Standards and Technology), and Dr Robert J. Trew (Office of the Secretary of Defense) for their excellent and continuous support of and participation in the WTEC study of spin electronics in the United States, Japan and Europe. The WTEC study of spin electronics could not have been so successfully conducted without the expertise and devotion to duty of WTEC personnel, especially Mr. Geoffrey M. Holdridge, WTEC Vice President for Operations and Dr. Robert D. Shelton, President of WTEC, and Mr. Horoshi Morishita, WTEC Japan representative for arranging the site visits. Also, I wish to acknowledge my colleagues at NSF (National Science Foundation), in particular Dr. Elbert L. Marsh and Dr. Rajinder P. Khosla, who gave of their time and effort to make the spin electronics study the great success that it has been. Finally, I would like to thank Dr. Russell J. Churchill at ARCOVA (American Research Corporation of Virginia) for technical discussions.

For my part, I am convinced that we are standing at the crossroads of two great technologies; namely, magnetics and semiconductor electronics, whose intersection has given rise to the new discipline that we know variously as spin electronics, spintronics, magnetoelectronics or magnetronics, and whose impact on the global economy and society in general can, at this time, only be imagined.

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FOREWORD

We have come to know that our ability to survive and grow as a nation to a very large degree depends upon our scientific progress. Moreover, it is not enough simply to keep abreast of the rest of the world in scientific matters. We must maintain our leadership.²

President Harry Truman spoke those words in 1950, in the aftermath of World War II and in the midst of the Cold War. Indeed, the scientific and engineering leadership of the United States and its allies in the twentieth century played key roles in the successful outcomes of both World War II and the Cold War, sparing the world the twin horrors of fascism and totalitarian communism, and fueling the economic prosperity that followed. Today, as the United States and its allies once again find themselves at war, President Truman's words ring as true as they did a half century ago. The goal set out in the Truman Administration of maintaining leadership in science has remained the policy of the U.S. Government to this day: Dr. John Marburger, the Director of the Office of Science and Technology (OSTP) in the Executive Office of the President made remarks to that effect during his confirmation hearings in October 2001.³

The United States needs metrics for measuring its success in meeting this goal of maintaining leadership in science and technology. That is one of the reasons that the National Science Foundation (NSF) and many other agencies of the U.S. Government have supported the World Technology Evaluation Center (WTEC) and its predecessor programs for the past 20 years. While other programs have attempted to measure the international competitiveness of U.S. research by comparing funding amounts, publication statistics, or patent activity, WTEC has been the most significant public domain effort in the U.S. Government to use peer review to evaluate the status of U.S. efforts in comparison to those abroad. Since 1983, WTEC has conducted over 50 such assessments in a wide variety of fields, from advanced computing, to nanoscience and technology, to biotechnology.

The results have been extremely useful to NSF and other agencies in evaluating ongoing research programs, and in setting objectives for the future. WTEC studies also have been important in establishing new lines of communication and identifying opportunities for cooperation between U.S. researchers and their colleagues abroad, thus helping to accelerate the progress of science and technology generally within the international community. WTEC is an excellent example of cooperation and coordination among the many agencies of the U.S. Government that are involved in funding research and development: almost every WTEC study has been supported by a coalition of agencies with interests related to the particular subject at hand.

The present study, reviewing the status of spin electronics research and development in the United States, Japan, and Europe, is a case in point. Support for this study came from NSF, the Defense Advanced Research Projects Agency, the Office of the Secretary of Defense, the Office of Naval Research, and the National Institute of Standards and Technology. The results of the study have already been incorporated to some degree in the content of a new NSF program announcement entitled, "Spin Electronics for the 21st Century."⁴ The findings of this study also have considerable bearing on the National Nanotechnology Initiative, which now is coordinating the nanoscale research and development activities and interests of 15 Federal agencies.

² Remarks by the President on May 10, 1950 on the occasion of the signing of the law that created the National Science Foundation. *Public Papers of the Presidents* 120: p. 338.

³ http://www.ostp.gov/html/01_1012.html.

⁴ See <http://www.nsf.gov/pubs/2002/nsf02036/nsf02036.html>.

Indeed, innovations in spin electronics may prove key to keeping the United States and the world on the path of ongoing progress in price and performance of electronic devices widely described as Moore's Law.⁵ Near-term applications include high-speed non-volatile memory devices for computing, and there are many other exciting possibilities in the longer term, perhaps even including quantum computing applications. It is especially important for U.S. researchers and policymakers to remain abreast of ongoing developments in this field in both Europe and Japan, and to work with our friends and colleagues around the world to move this field forward for our mutual benefit. This WTEC report is one step in that direction.

As President Truman said over 50 years ago, our very survival depends upon continued leadership in science and technology. WTEC plays a key role in determining whether the United States is meeting that challenge, and in promoting that leadership.

Elbert Marsh
Deputy Assistant Director for Engineering
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⁵ See the Executive Summary of this report (p. xi) for a discussion of Moore's Law and its relationship to spin electronics research.

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